NDCX-II, an Induction Linac for HEDP and IFE Research

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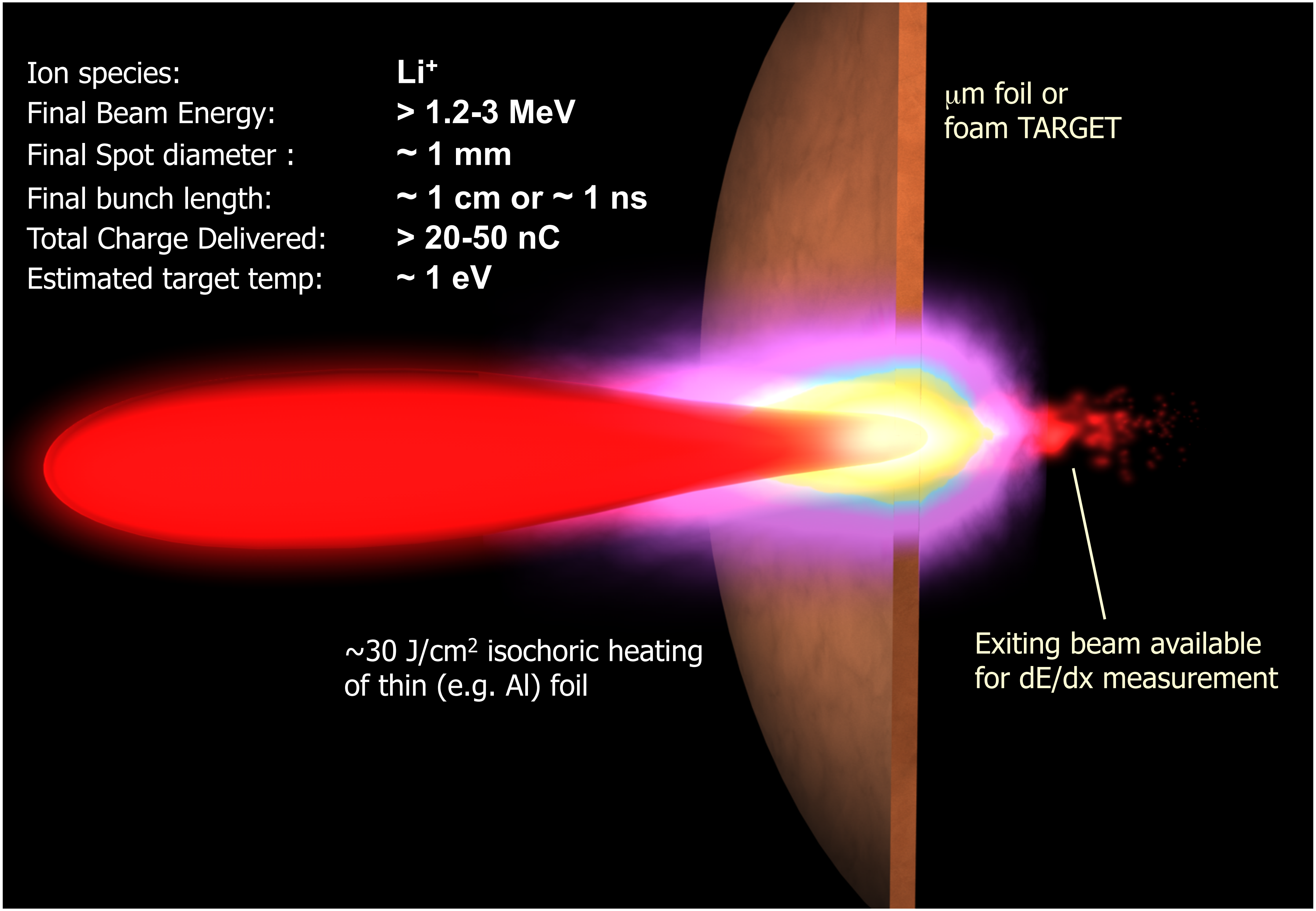
Outline

- Scientific Motivation and Historical Background
- NDCX-II Project
  – Approaches
  – Physics design
  – Accelerator system
  – Progress
  – Technical Challenges
- Summary

NDCX-II is ideally suited for heating foils to WDM regime



NDCX-II uses a Li^{+} ion beam at near Bragg Peak energy

Near constant dE/dx at Bragg peak, at 2 MeV for Li ions

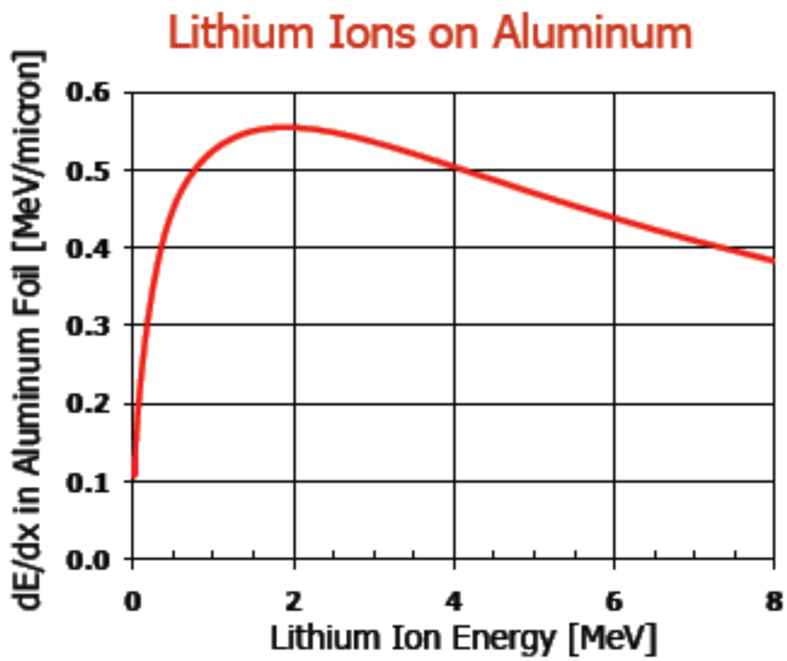


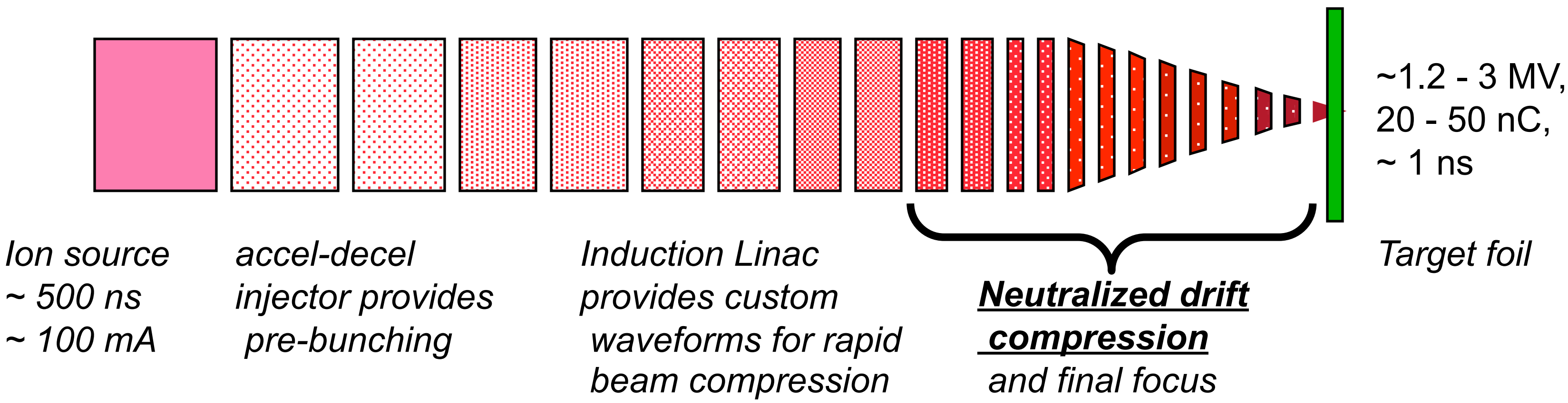
Figure from R. Lee

For < 1 MeV, can use lighter ions, e.g. He+
For > 10 MeV, can use heavier ions, e.g. C+

NDCX-II is an induction accelerator that can compress beam pulses

Key Concept:

- “Velocity tilt” produces longitudinal compression, 500 ns → 1 ns.
- High-field solenoid to focus the very high line charge-density.
- Neutralized final focusing to a 1 mm spot size on target.

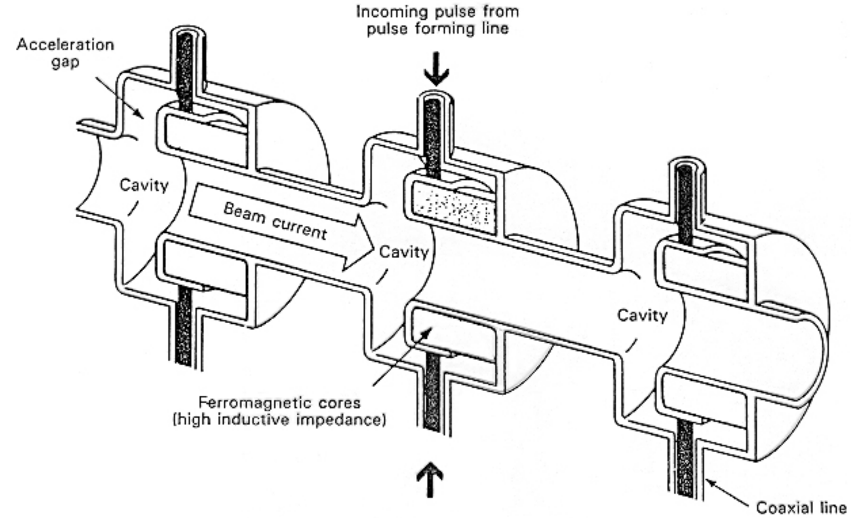


Key design parameters:

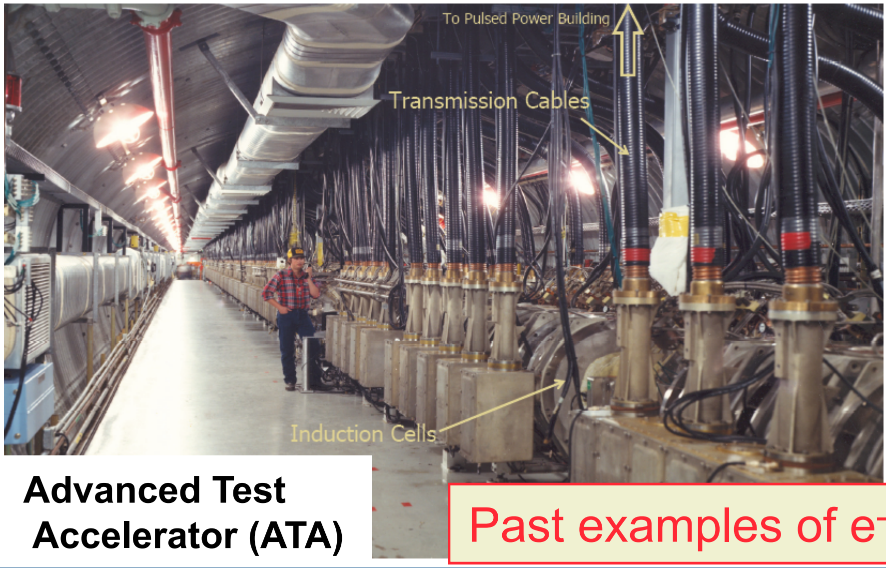
- Li^+ Ion source at ~ 1 mA/cm^2.
- Each induction cell provides up to 250 kV x 70 ns volt-seconds.
- Build new 2.5 T pulsed solenoids for beam transport.
- Use an existing 8 T solenoid for final focus.

Induction linacs are ideal for high-current short-pulse beams

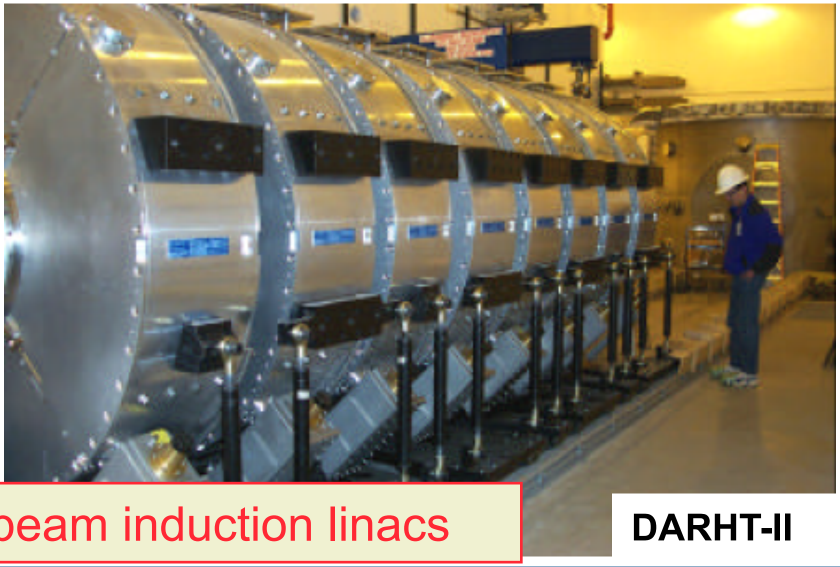
- An induction linac works like a series of transformers using the beam as a "single-turn" secondary.
- Volt-seconds in the core material limits the pulse length.
- Applied voltage waveforms determine the acceleration schedule.



Schematic cutaway of an induction Linac



Advanced Test Accelerator (ATA)



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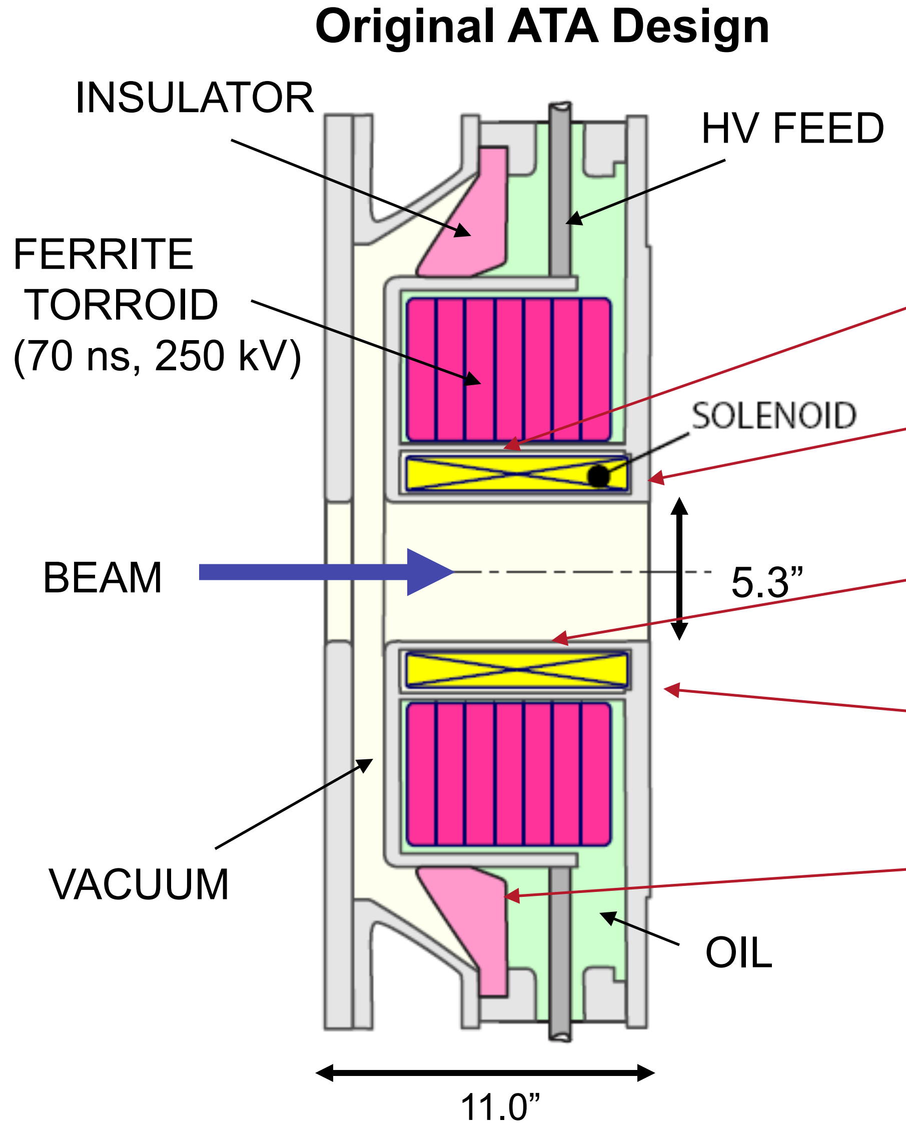
Past examples of e^- beam induction linacs

Modify the ATA cell—build pulsed solenoid and smaller bore



Modifications:

Add Cu cylinder to shield stray magnetic field

Replace with 2.5 T Pulsed Solenoid

Reduce beam tube diameter to 3.1”

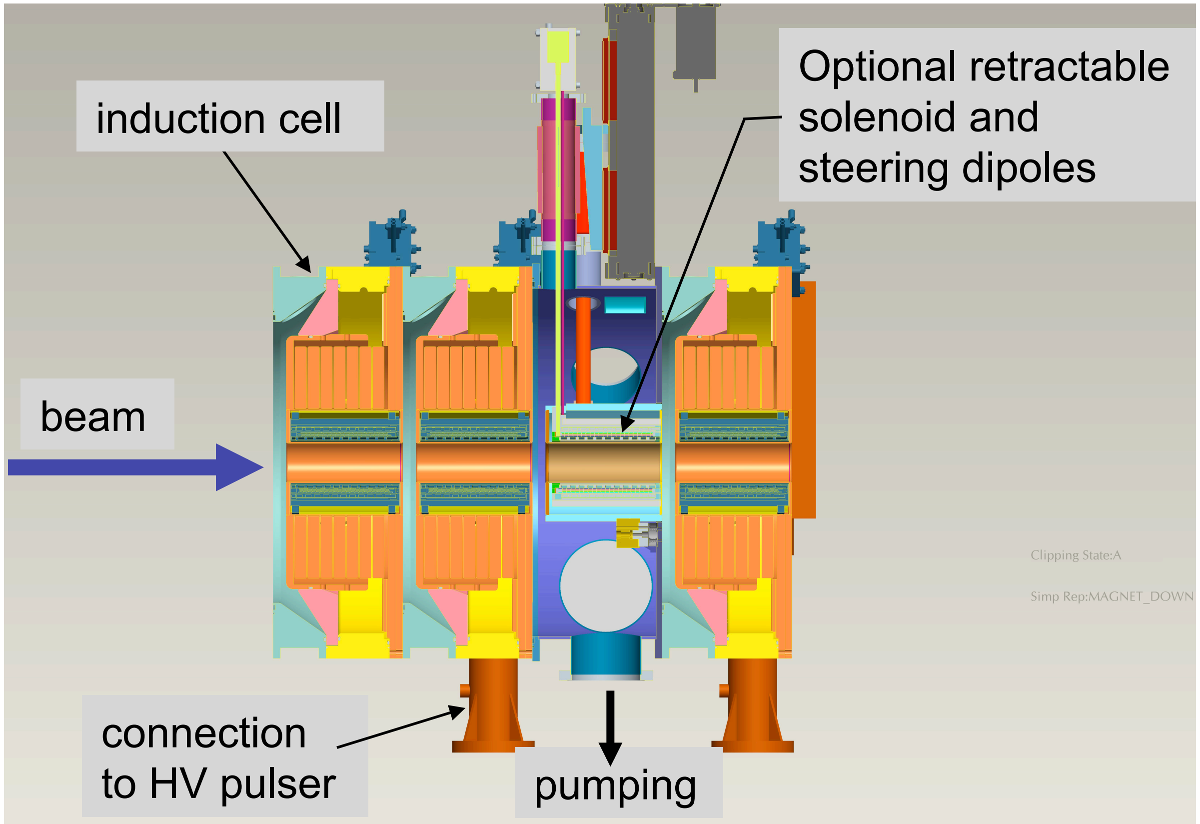
Use thinner flanges to reduce eddy current

New Rexolite insulator

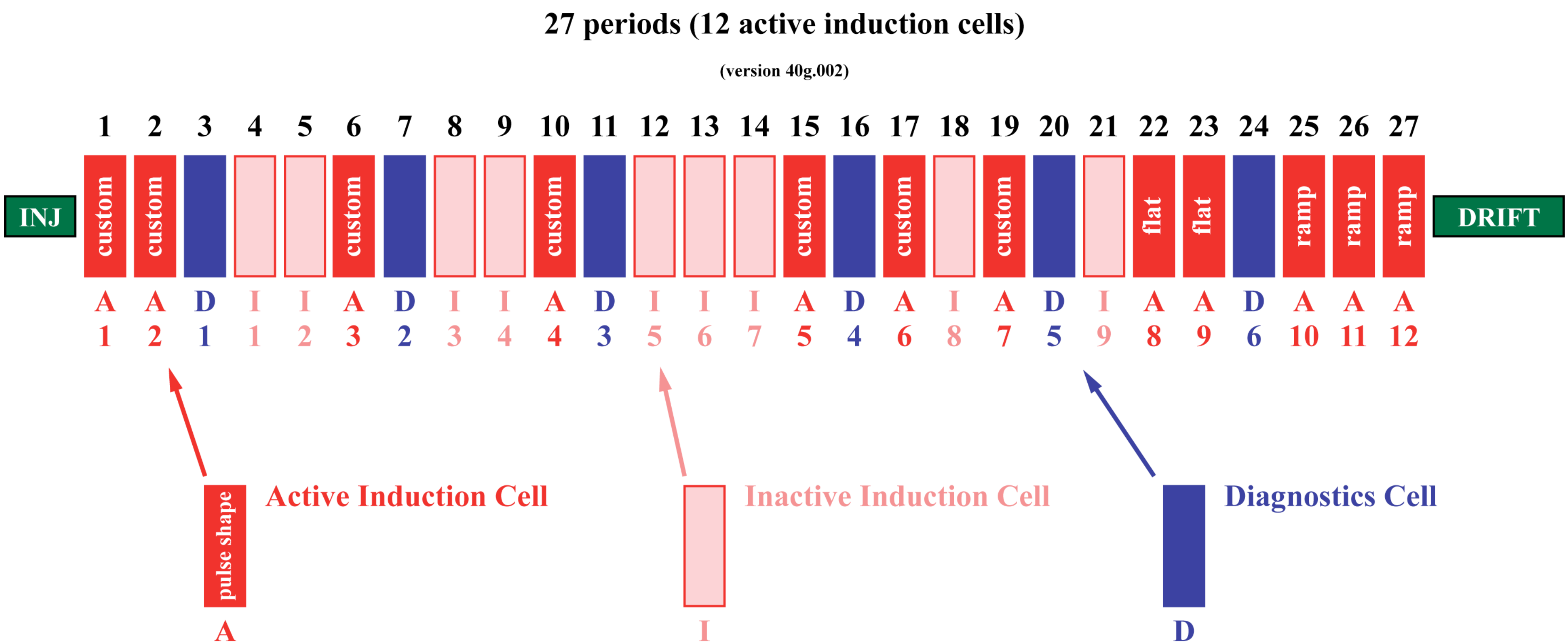
See details in Leitner’s talk

NDCX-II Induction Cell Detailed Design

- "Active" induction cells for acceleration
- Non-active cells for drift space, beam steering and diagnostics.

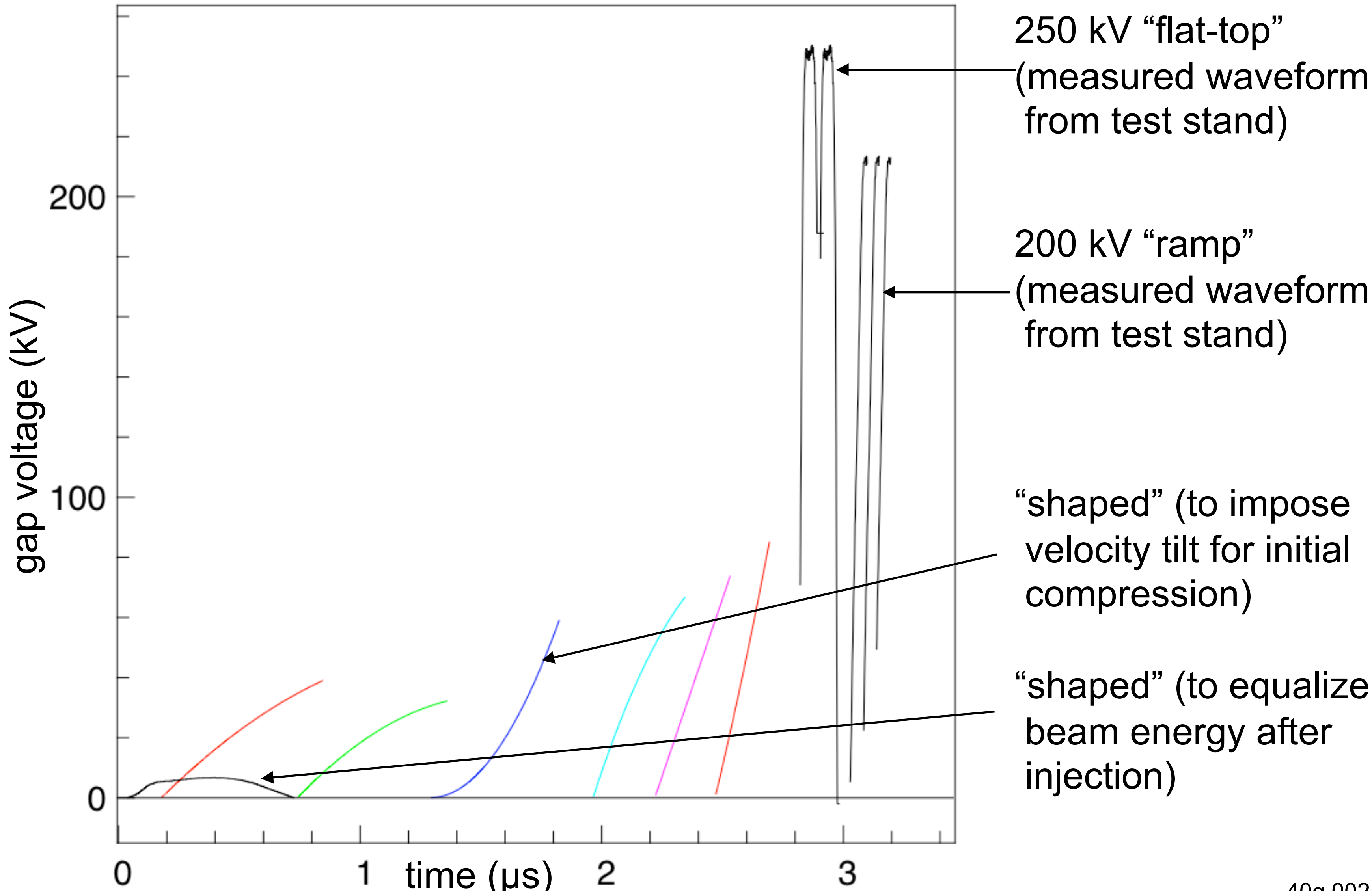


The NDCX-II baseline physics design effectively combines acceleration and drift-compression



Active induction cells are driven by one of three pulsed power systems:
- custom: moderate-voltage power supply
- flat: Blumlein-driven 250 kV flat-top (data from test stand)
- ramp: Blumlein-driven ramp to 200 kV (data from test stand)

Voltage waveforms for all gaps



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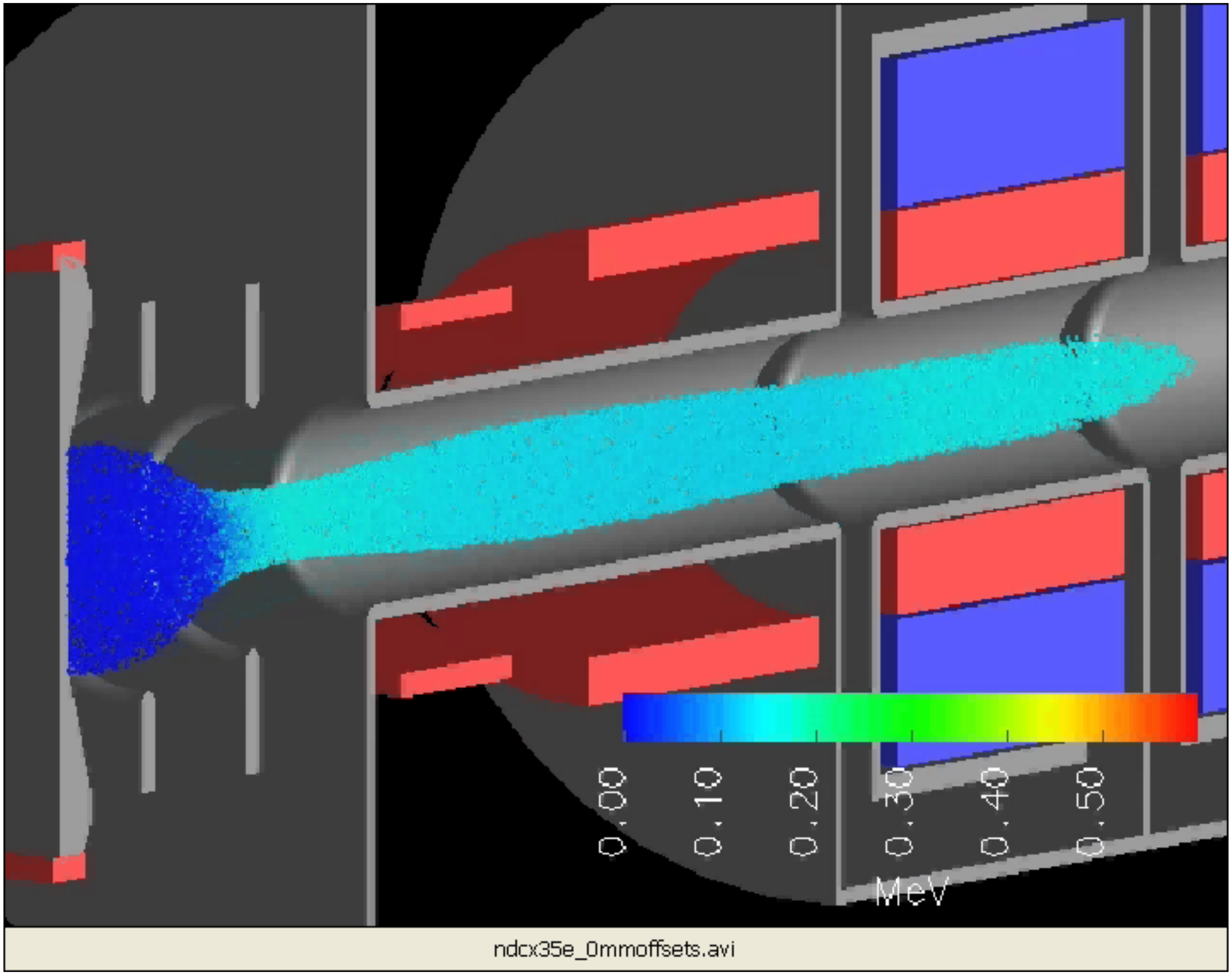
Beam line design makes heavy use of computer simulations

- Run 1-D Particle-in-cell (PIC) code with a few hundred particles for design synthesis:
  - Models gaps as extended fringing field.
  - Self-field model guided by results from Warp runs.
  - Can use realistic acceleration waveforms.
  - Also include centroid tracking for study of misalignment effects.

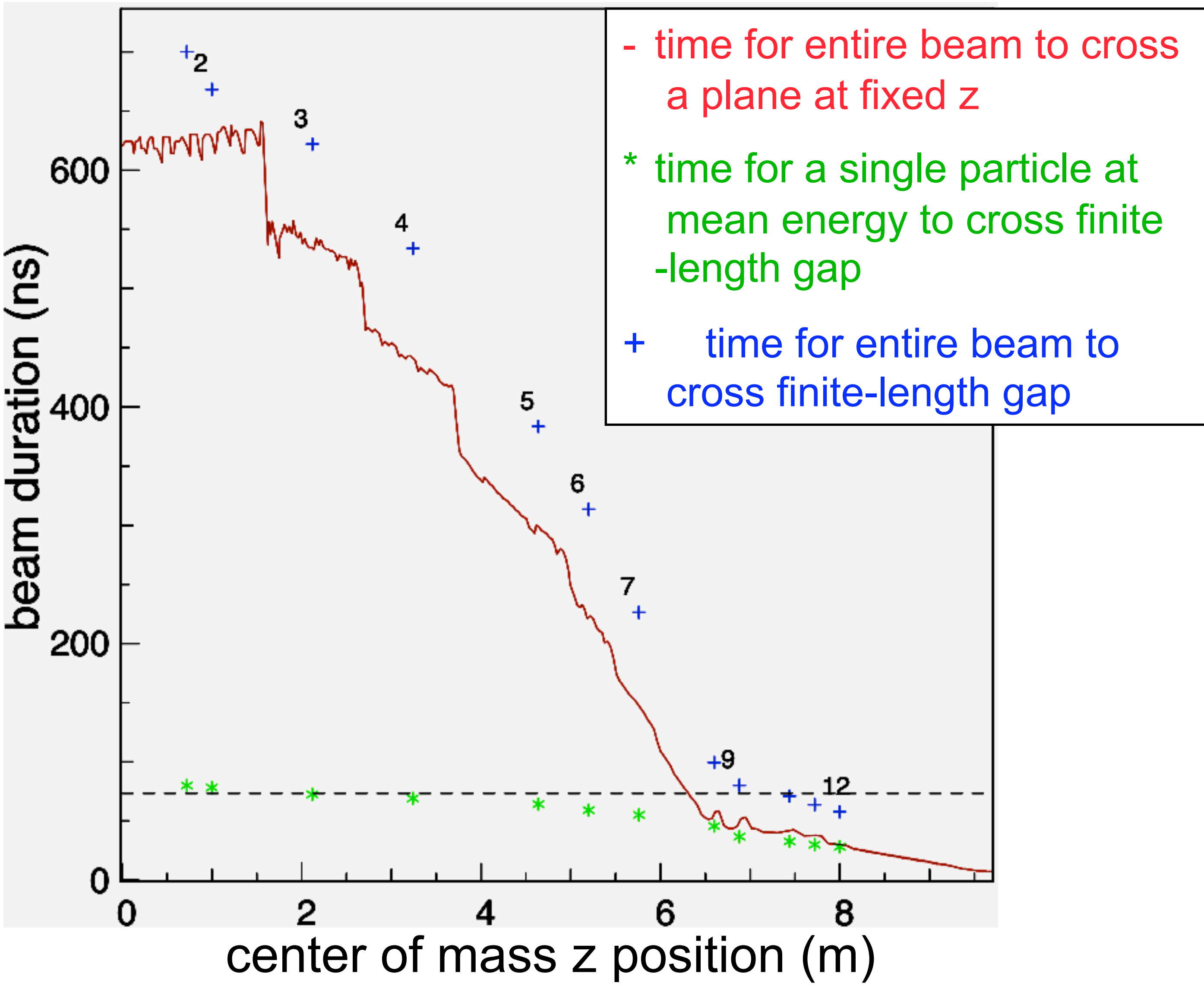
- Run comprehensive PIC code "Warp" for detailed design:
  - 3-D and axisymmetric (r,z) models.
  - Electrostatic space charge and accelerating gap fields included.
  - Time-dependent space-charge-limited emission.
  - Extensively benchmarked against experiments and analytic cases.

3-D Warp End-to-End Simulation



See details in Dave Grote

Pulse duration vs. z: the entire beam transit time is key



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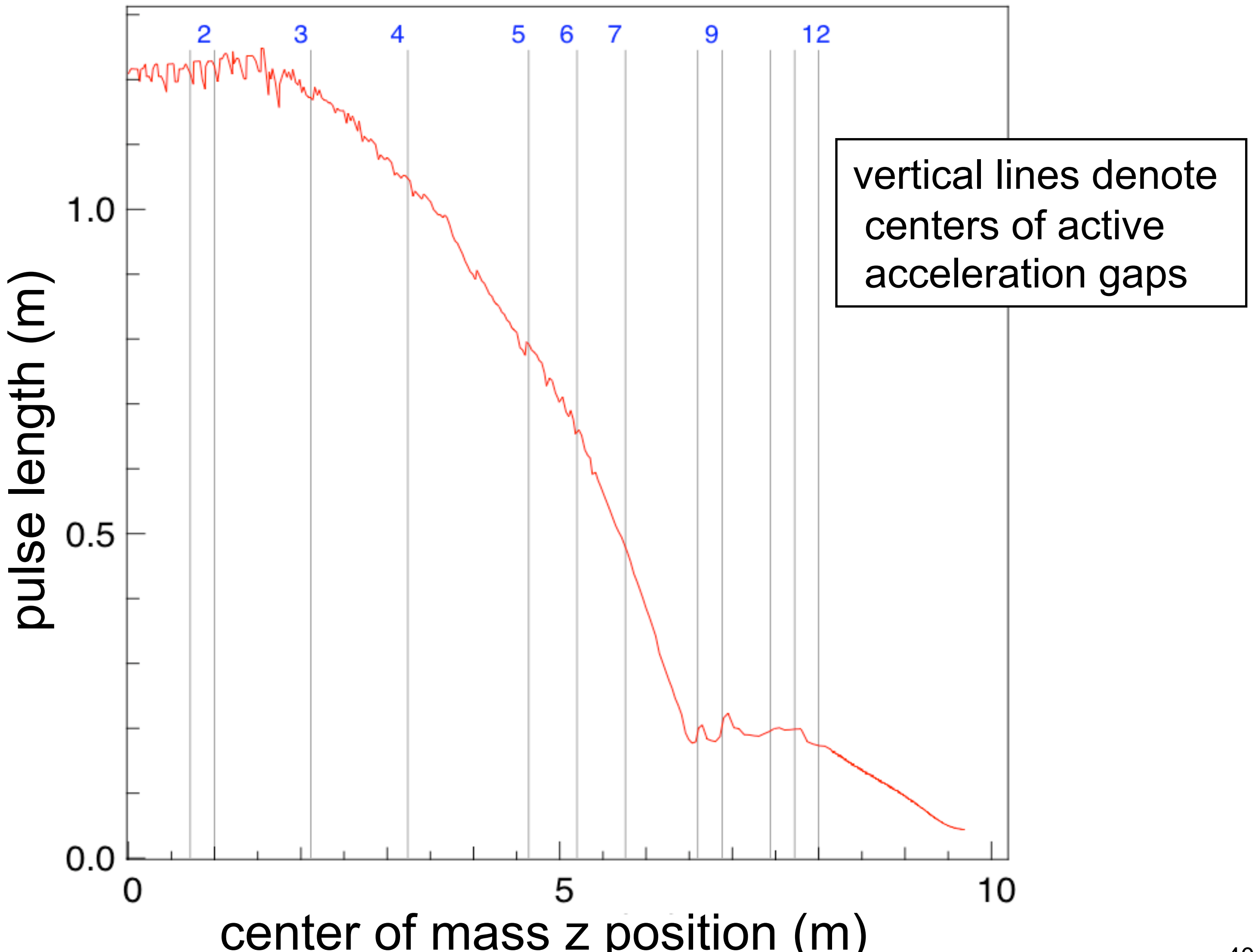
Pulse length vs. z, as developed using 1-D ASP simulation



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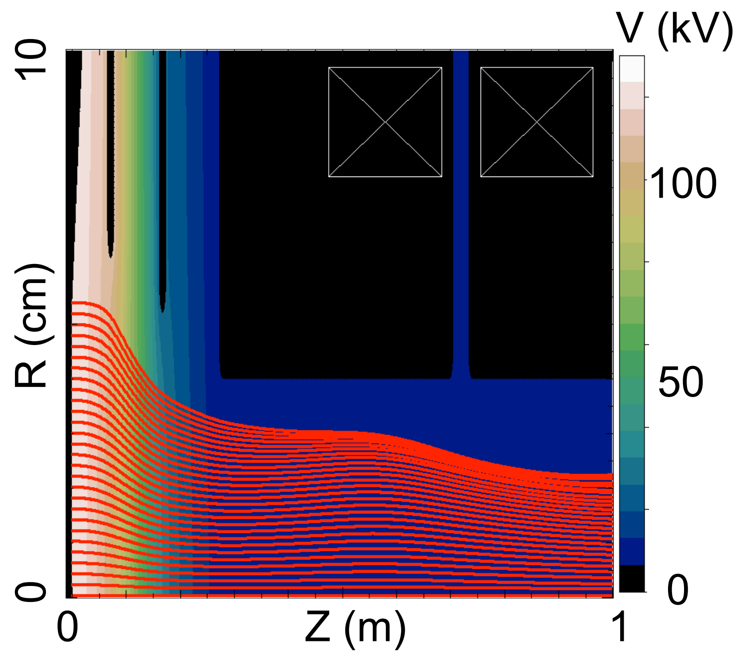
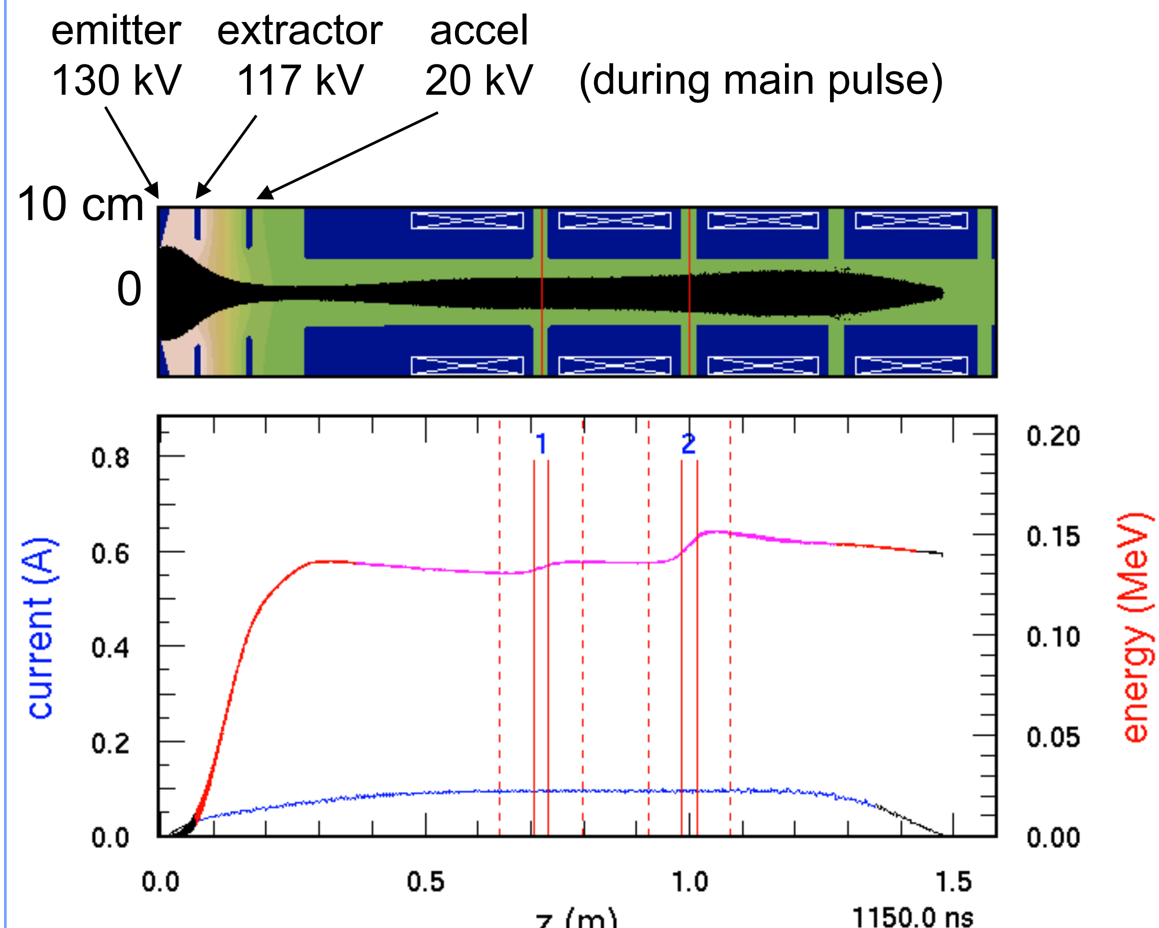
NDCX-II injector is based on a 1 mA/cm² Li^+ ion source

First, used Warp code's steady-flow "gun" mode in (r,z) geometry; adjusted injector and solenoid parameters for laminar flow:



Second, carried out fully time dependent simulation:



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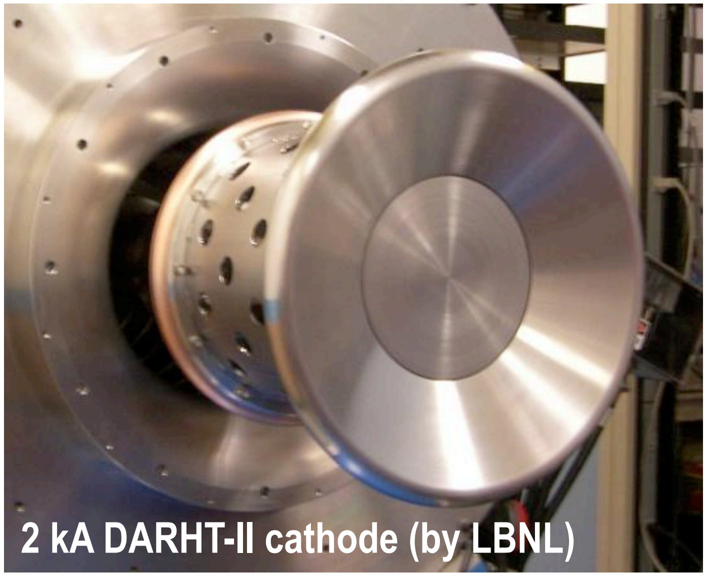
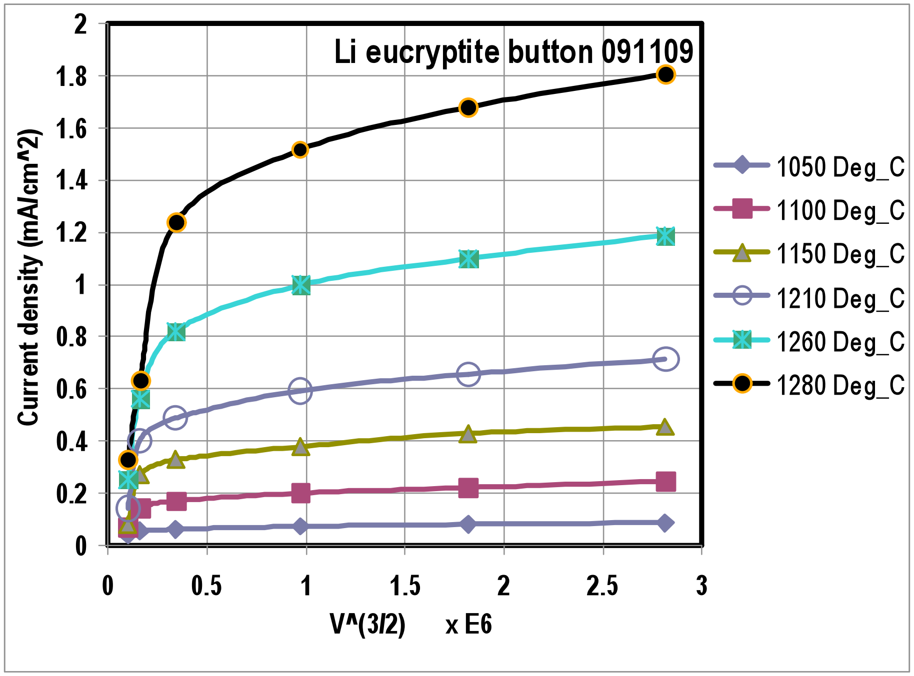
We are developing a high current Li^+ ion source for NDCX-II

- LBNL's HIFS program has been making large hot-plate sources for more than 20 years, e.g. the 6.7 inches diameter K^+ ion source for HCX.
- The Li^+ alumino-silicate (hot-plate) ion sources for NDCX-II is similar to the K^+ one for NDCX-I, except being larger and runs at high temperature.
- On-going emission and life time test using quarter-inch samples
  - our data showed Li^+ current density > 1 mA/cm^2 at T ~ 1280 deg C

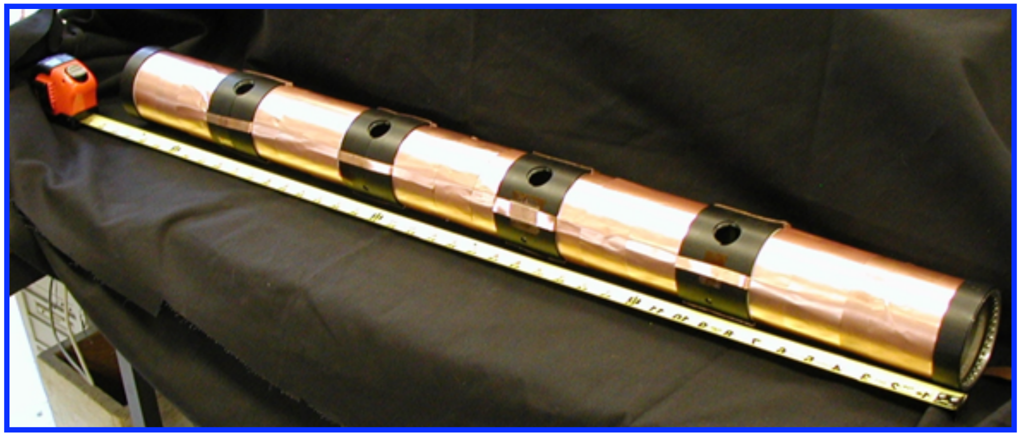
See details in Prabir Roy



The NDCX-II source will be ~ 10.9-cm dia.



NDCX-II beam neutralization is based on NDCX-I experience



For the drift compression region, use existing high-dielectric ferroelectric ceramics plasma source technology

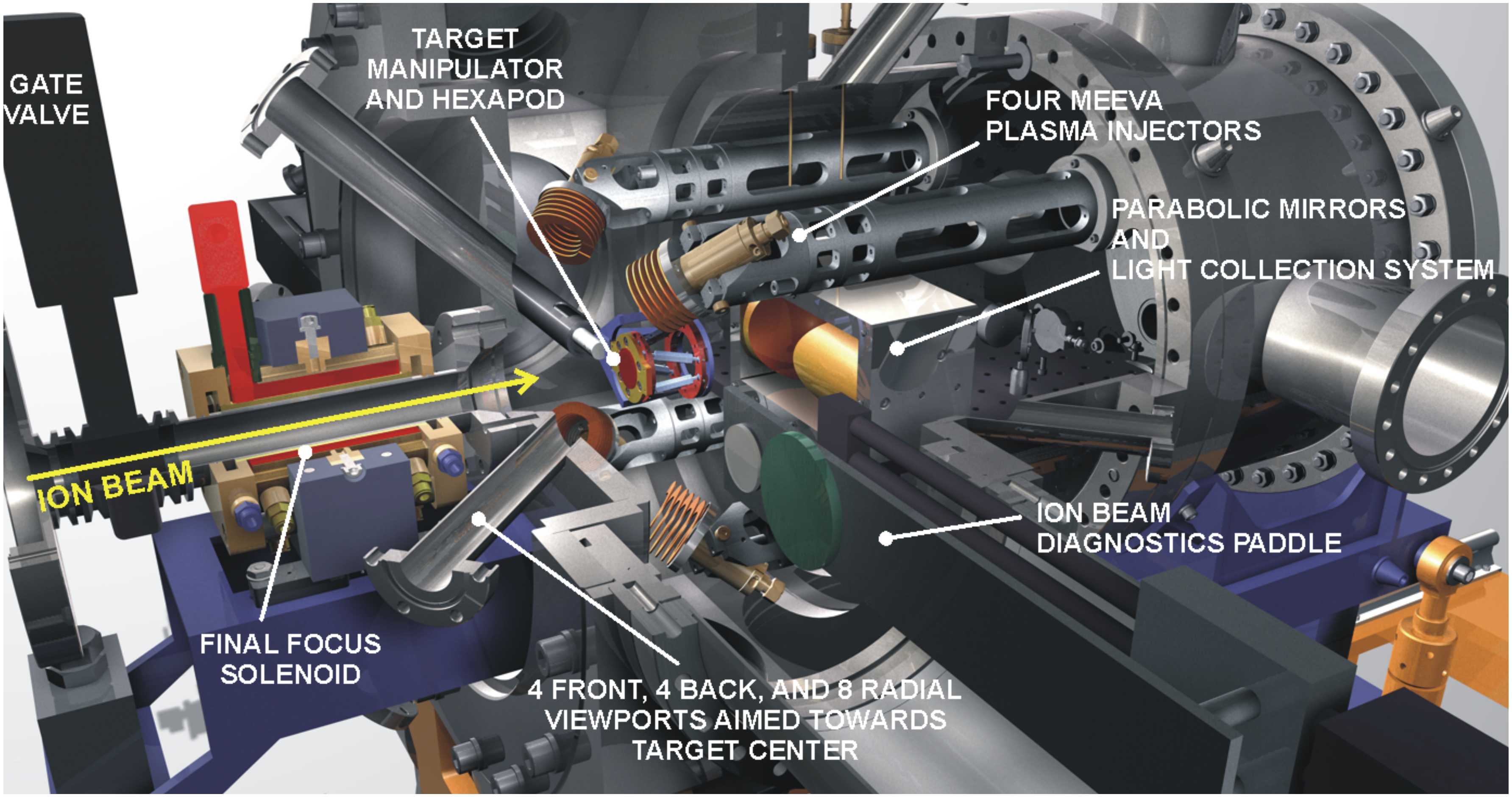
Expects:
> 50,000 shots with $N_e \sim 10^{10}$ /cm^3

For the target region, use cathodic-arc plasma source

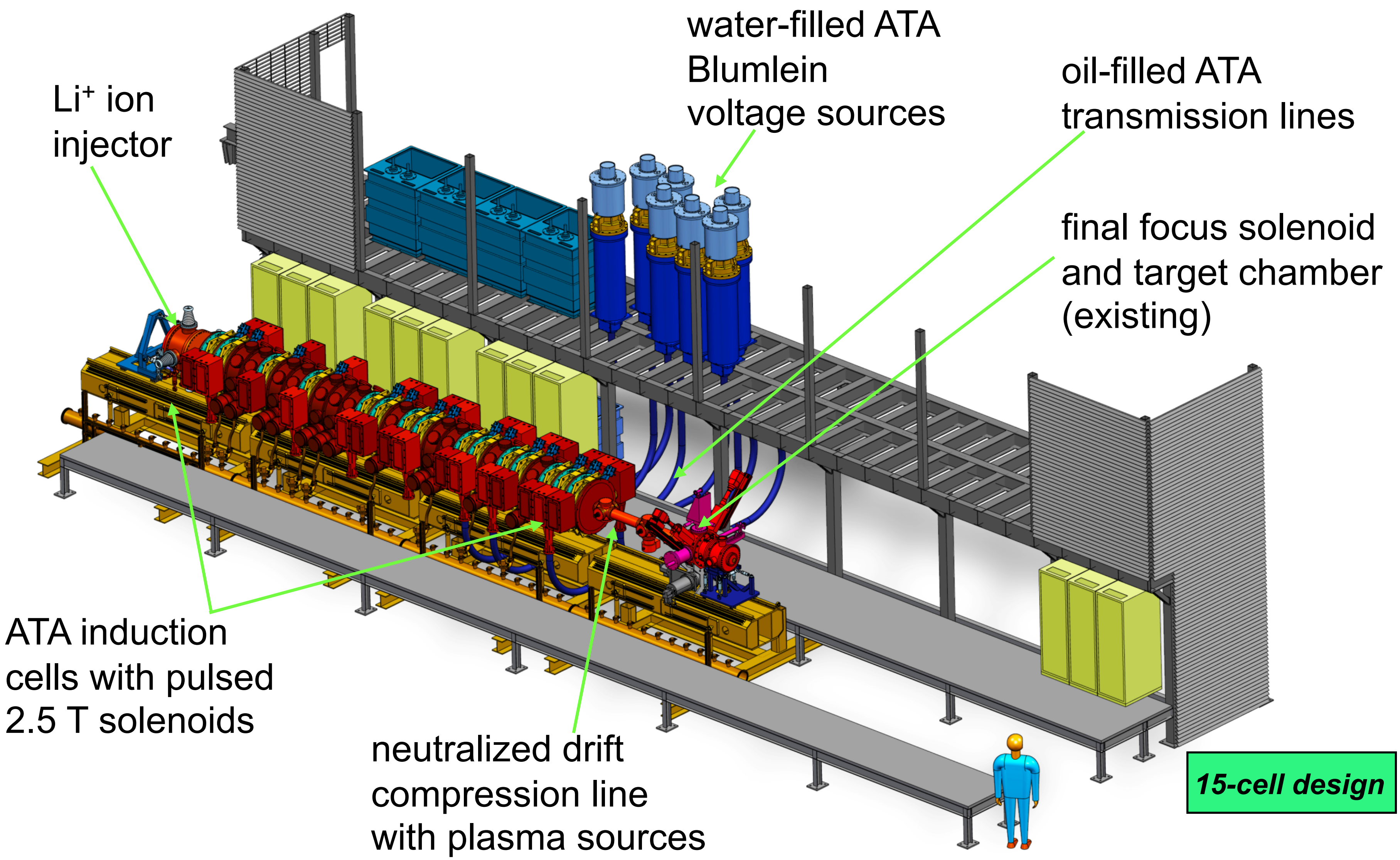
Expects:
partial neutralization at the final ~1 cm with $N_e \sim 10^{14}$ /cm^3

See details in Erik Gilson (PPPL)

Initially NDCX-II will reuse the same NDCX-I target chamber



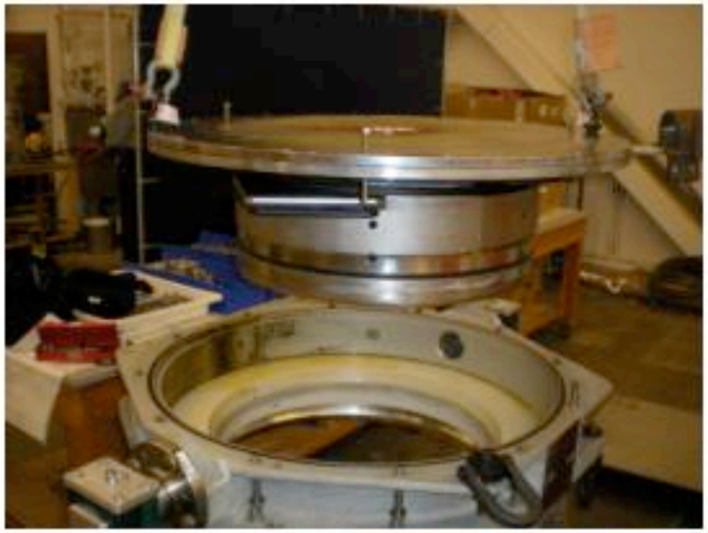
NDCX-II Machine Layout

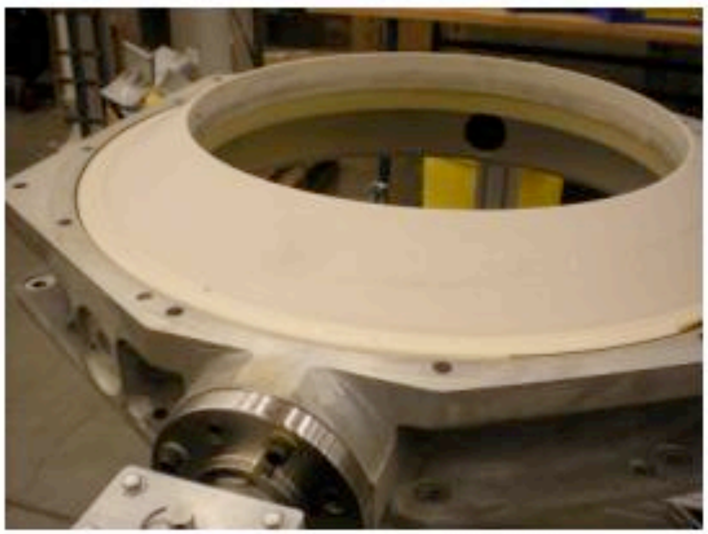


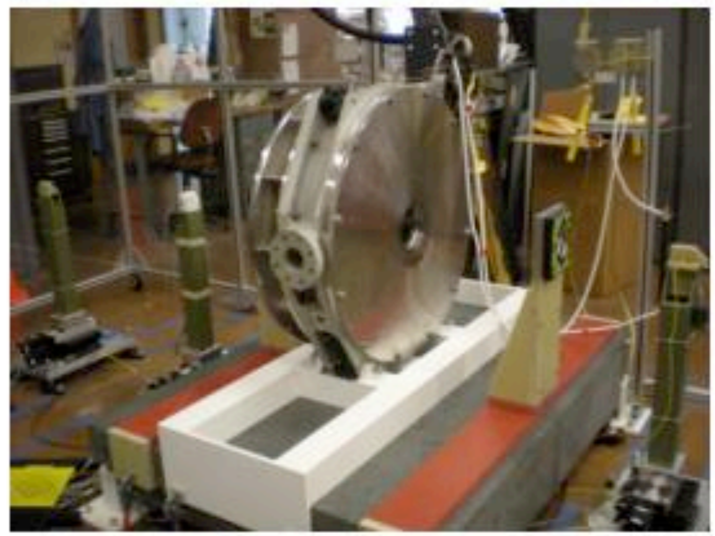
NDCX-II accelerator parameters

Parameter	Value
Lattice Period	11 inch (27.94 cm)
Beam Pipe Radius	1.562 inch (3.97 cm)
Solenoid Field	2.5 Tesla peak field
Steering Coil	0.025 Tesla
Maximum Repetition Rate	once every 30 seconds
Beamline Vacuum	$< 1.0 * 10^{-6}$ mbar
Alignment (Magnetic Center)	within 0.020 inch (0.5 mm) of nominal position
Peak Cell Voltage Capability	250 kV @ 70 ns (FWHM)
Injector Current Density	> 1.0 mA/cm^2

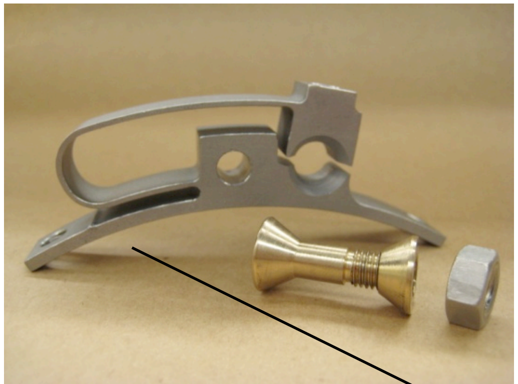
The induction cells fabrication and alignment have begun

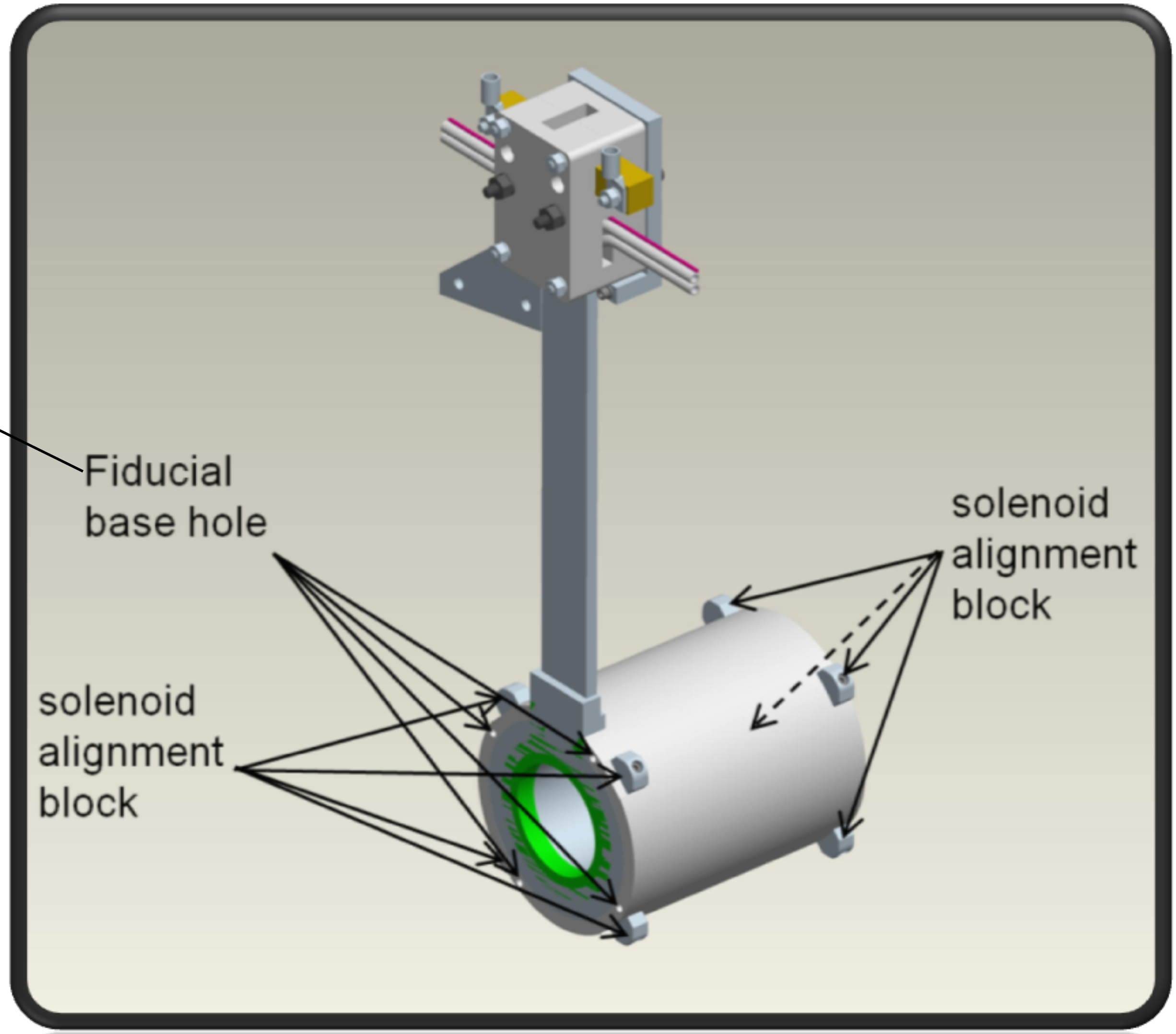




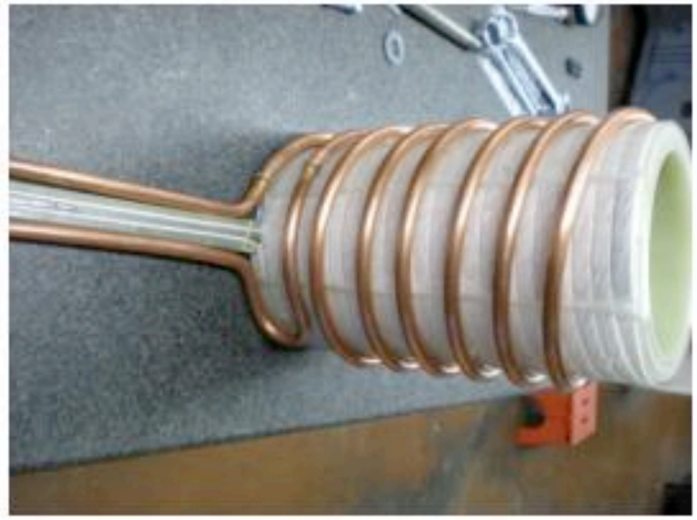


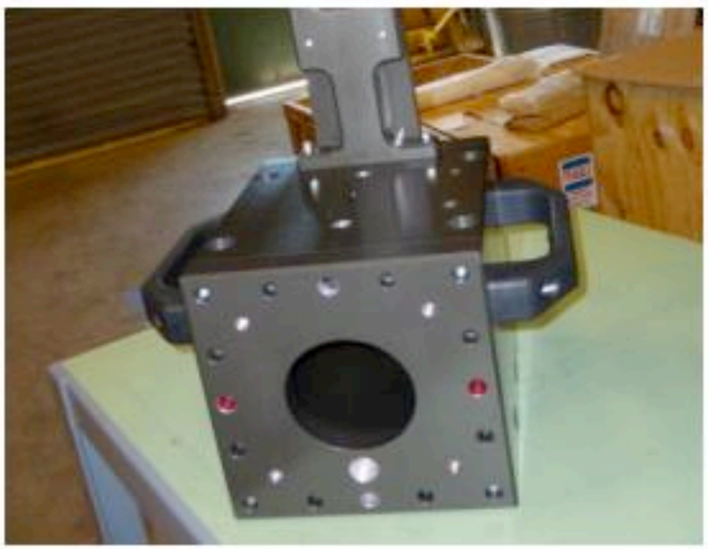
The NDCX-II cell solenoid design



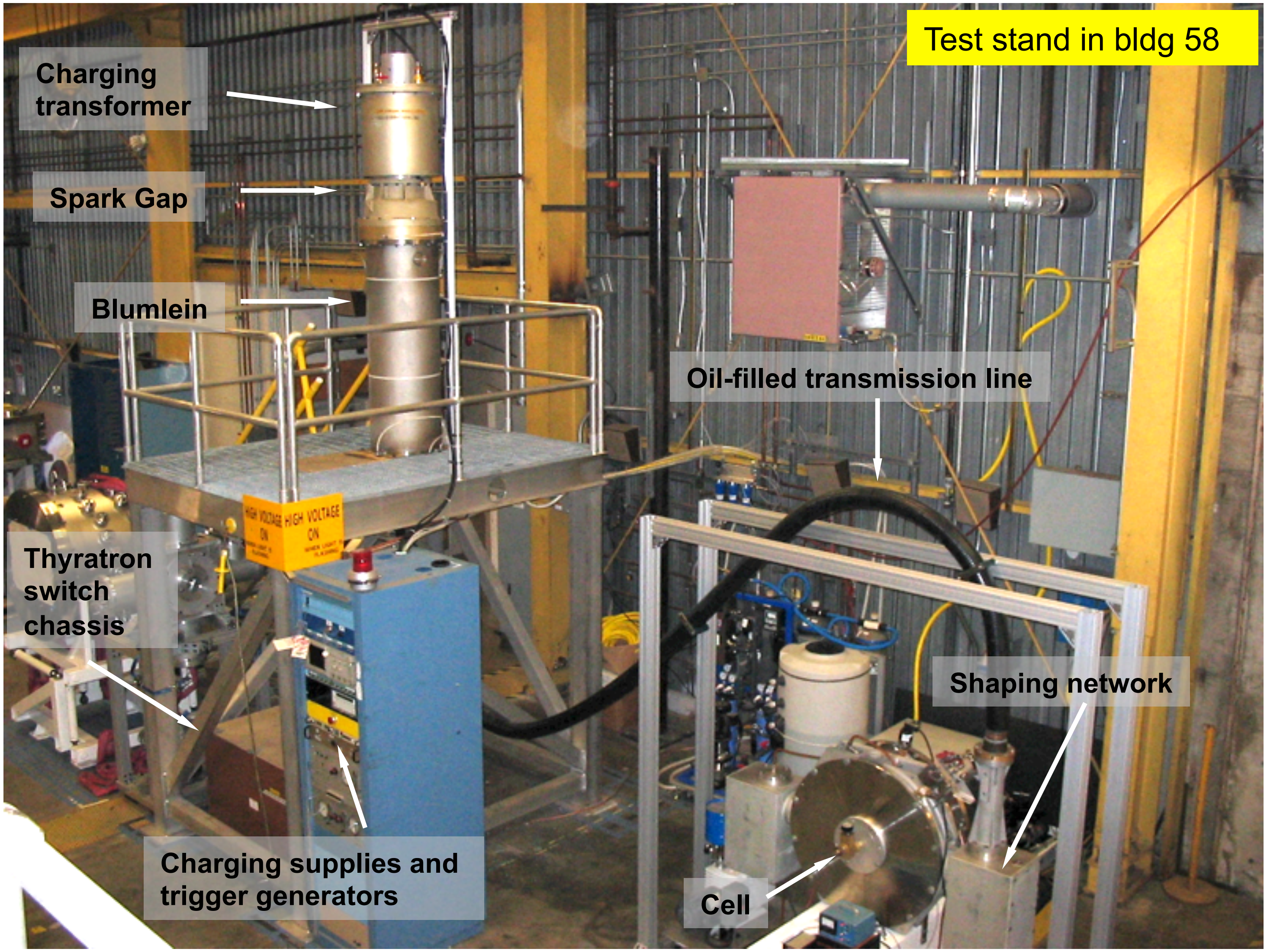


Fabrication of the focusing solenoids

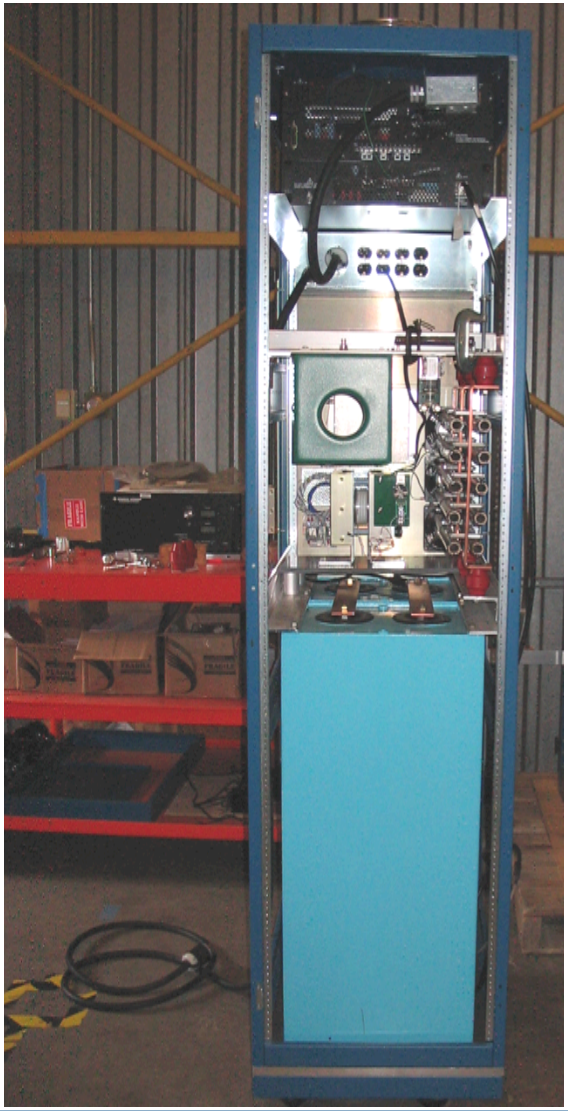




Produce Custom Voltage Waveforms from Blumlein



Prototypes of High current magnet pulser systems

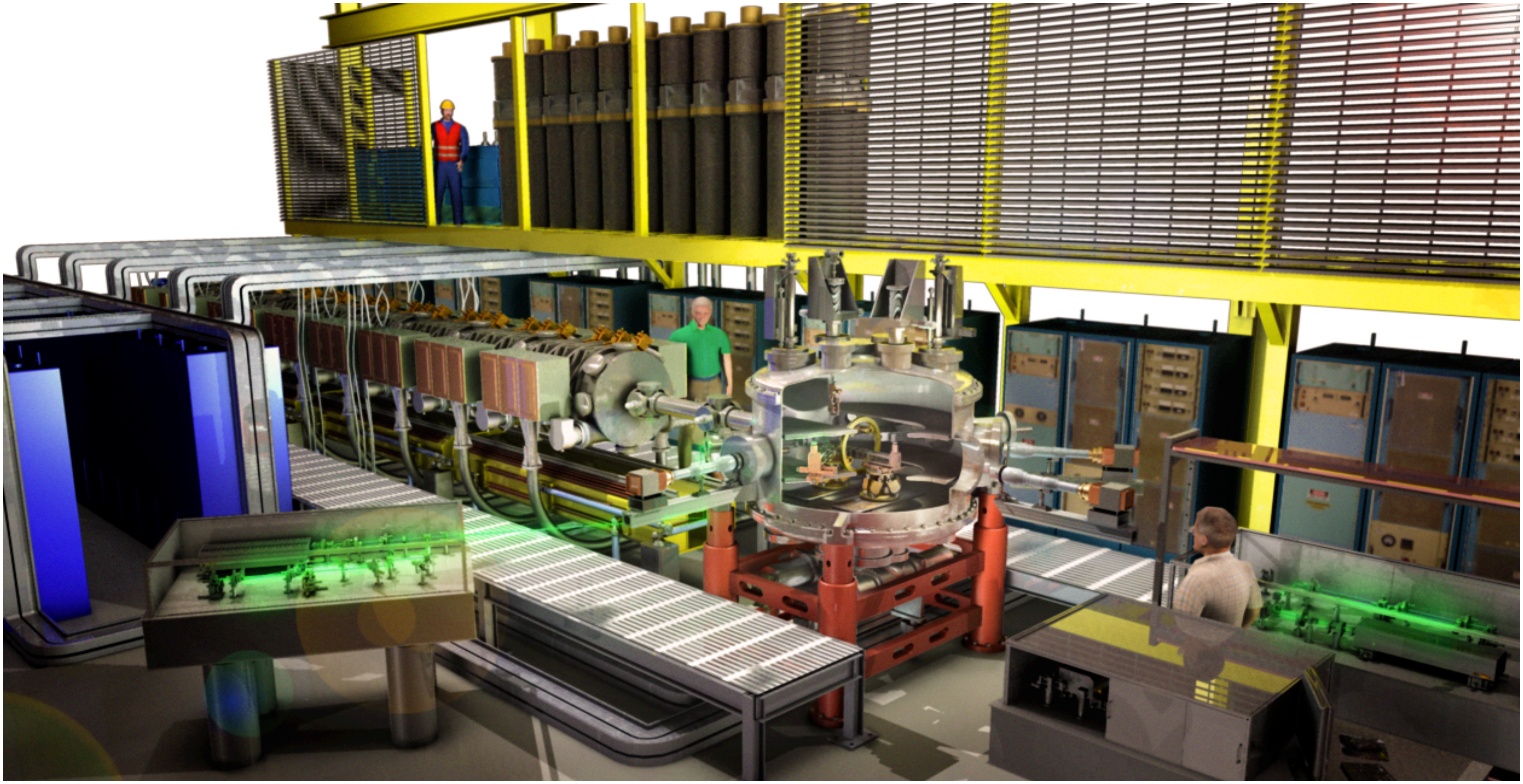


Technical Challenges and Other Risks

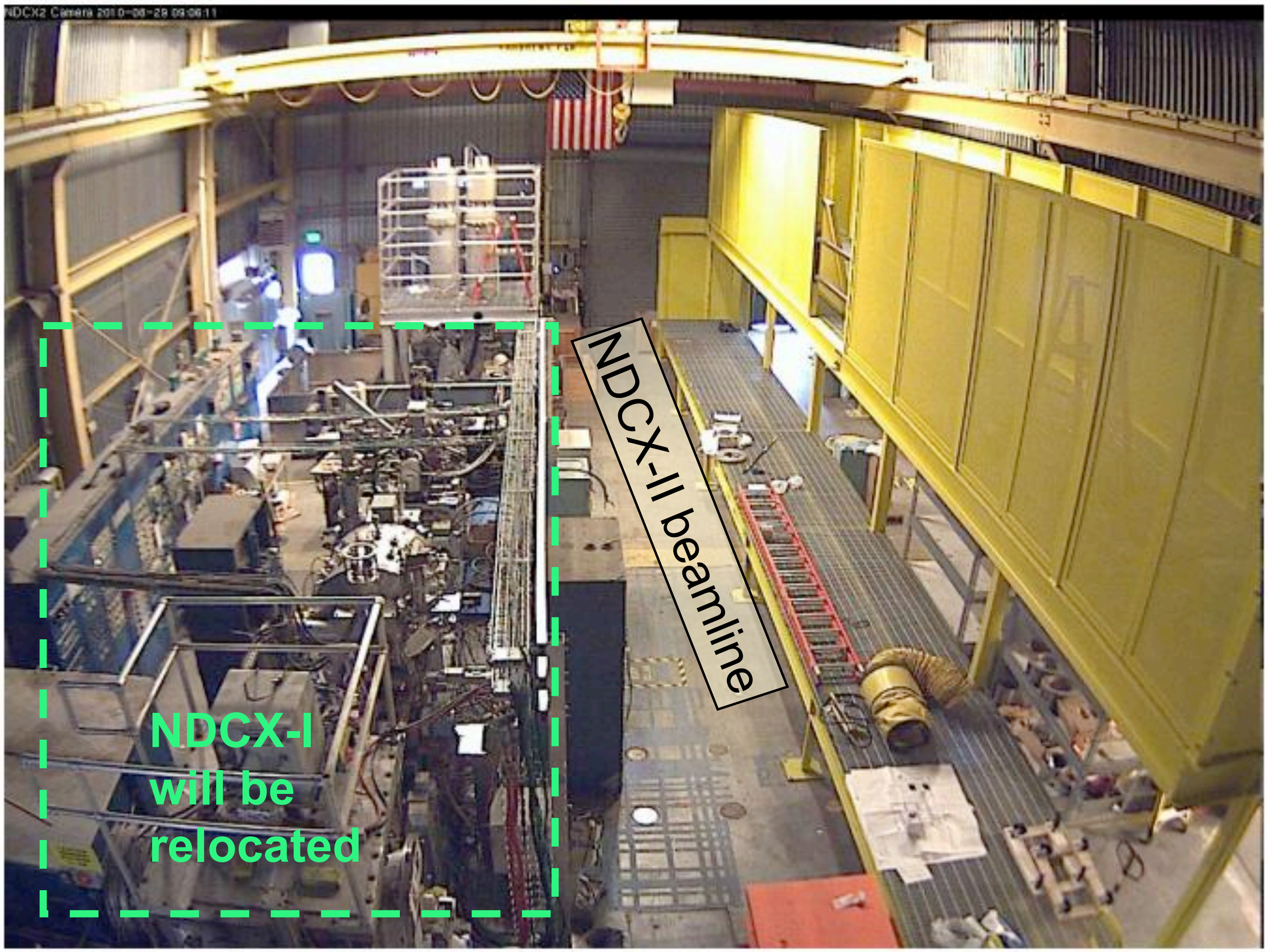
- **Ion source**: Li^+ current density of > 1 mA/cm^2 has been obtained, and we are continuing R&D in our base program.
- **Injector**: Design for high temperature (1280ºC) operation and short life time of ion source requiring quick replacement.
- **Custom voltage waveforms for ion acceleration**: Sensitivity studies (simulations) and experimental tests have confirmed feasibility.
- **Solenoid magnet alignment**: mechanical alignment technique was confirmed, and provide beam steering correction using dipole coils.
- **Transient field from the pulsed solenoid and correction dipole at the ferrite cores**: a copper shield was proved to be effective.
- **Electrical noise affecting beam diagnostics**: will require careful shielding of stray fields.

The NDCX-II Project for HEDLP/HIF Studies

Budget = $11M, Schedule = Jul 2009 to Mar 2012



Location of NDCX-II in Bldg-58 at LBNL



Aug 29, 2010

NDCX-II will be far more capable than NDCX-I

	NDCX-I (typical bunched beam)	NDCX-II 12-cell (r,z simulation)
Ion species	K^+ (A=39)	Li^+ (A=7)
Total charge	15 nC	50 nC
Ion kinetic energy	0.3 MeV	1.25 MeV
Focal radius (containing 50% of beam)	2 mm	0.6 mm
Bunch duration (FWHM)	2 ns	0.6 ns
Peak current	3 A	38 A
Peak fluence (time integrated)	0.03 J/cm^2	8.6 J/cm^2
Fluence within a 0.1 mm diameter spot	0.03 J/cm^2 (50 ns window)	5.3 J/cm^2 (0.57 ns window)
Fluence within 50% focal radius and FWHM duration ($E_{kinetic}$ x I x t / area)	0.014 J/cm^2	1.0 J/cm^2

NDCX-II estimates are from (r,z) Warp runs (no misalignments), and assume 1 mA/cm^2 emission, no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, perfect neutralization, and a uniform non-depleted source; they also assume no fine energy correction (e.g., tuning the final tilt waveforms)

Experiments Planned for NDCX-II

- Examine basic physics of warm density matter regime (kT ~ 1 eV), e.g., EOS, conductivity, liquid -vapor metal phase transition.
- Positive-negative halogen ion plasma (kT ~ 0.4 eV).
- Ion-beam-driven IFE-relevant target physics, e.g., ion coupling efficiency to an ablating plasma, and the hydro-dynamics.
- Study space-charge-dominated ion beam dynamics and the effects of secondary electrons in the accelerator.
- Study collective beam-plasma interaction processes, beam focusing, and compression in a neutralizing background plasma.

Figure from R. Lee

Conclusion

- NDCX-II will be a novel and flexible ion-driven user facility for warm dense matter and IFE target physics studies.

- The machine will also allow beam dynamics experiments relevant to high-current fusion drivers, e.g., beam pulse compression of 500 ns → 1 ns, and 110 mm → 1 mm.

- If more money is available:
  (1) installing additional induction cells to raise the beam energy. Since beam pulse is already compress, energy gain is cost effective at ~$100k per cell for each 200 kV.
  (2) Built a new target chamber

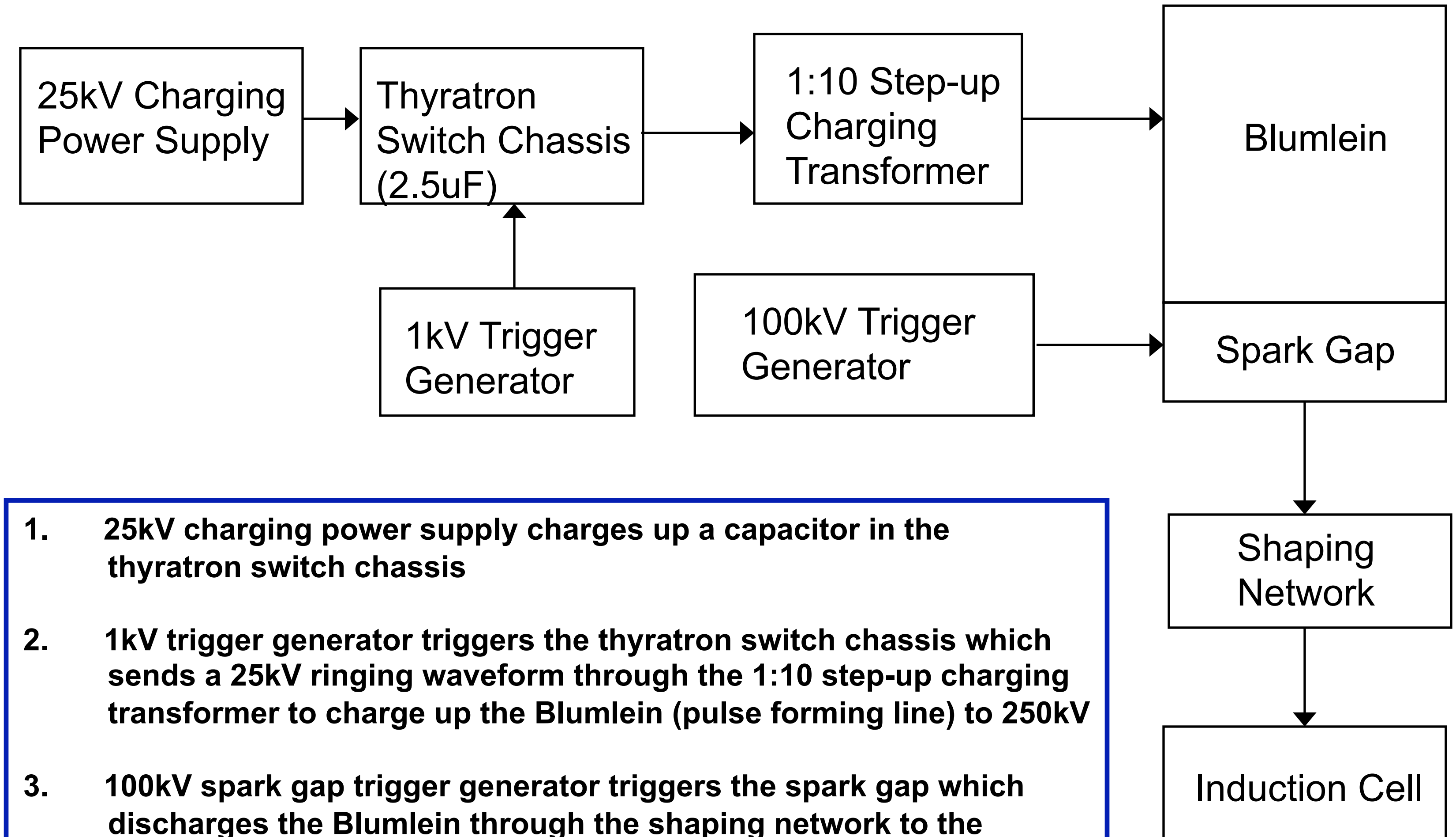
- NDCX-II is a prerequisite for the Integrated Beam–High Energy Density Physics Experiment in the 2007 DOE Office of Science Strategic Plan.

Back Up Slides

Fabrication, Installation and Integration

- **In-house fabrication (at LBNL):**
  - Solenoids, induction cell housing modification
  - HV pulsers for compression cells, solenoids, and steering coils,
  - Control system software
- **Major procurements**
  - Vacuum chambers, pumps, insulators, girders, support structures,
  - HV charging power supplies, spark gap trigger generators, capacitors, data acquisition and timing system
- **Installation and Integration**
  - Component testing (for QA)
  - Accelerator assembly
  - Accelerator magnetic axis alignment
  - Labview/EPICS-based control system

Blumlein Section Pulsed Power Block Diagram

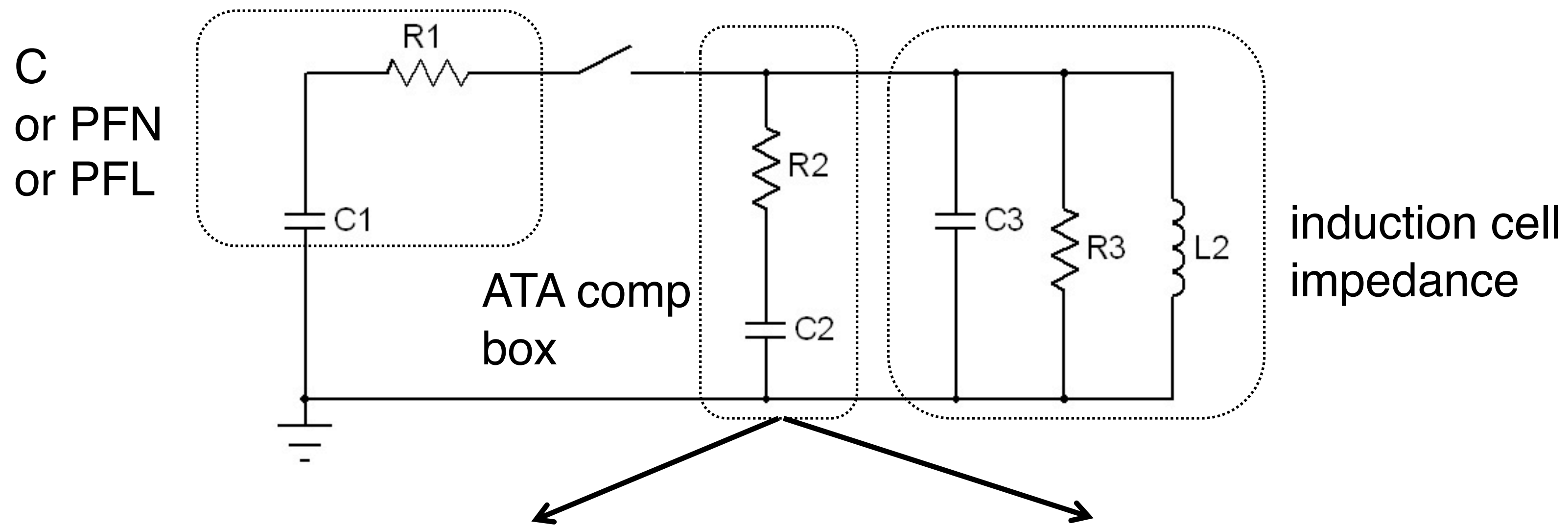


1. **25kV charging power supply charges up a capacitor in the thyratron switch chassis**

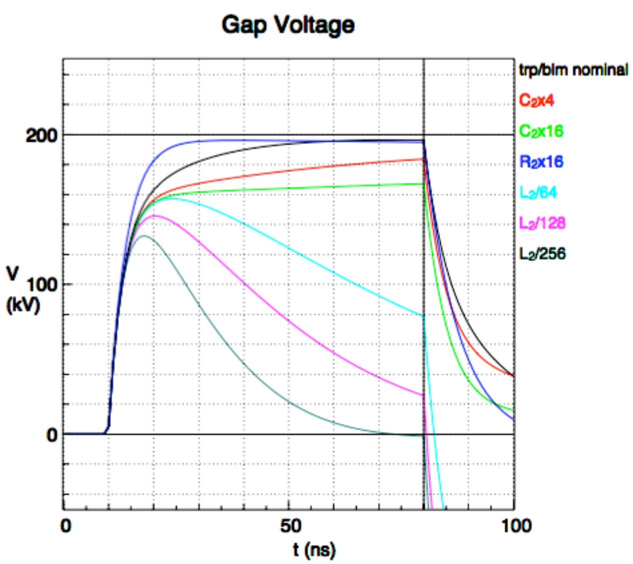
2. **1kV trigger generator triggers the thyratron switch chassis which sends a 25kV ringing waveform through the 1:10 step-up charging transformer to charge up the Blumlein (pulse forming line) to 250kV**

3. **100kV spark gap trigger generator triggers the spark gap which discharges the Blumlein through the shaping network to the induction cell**

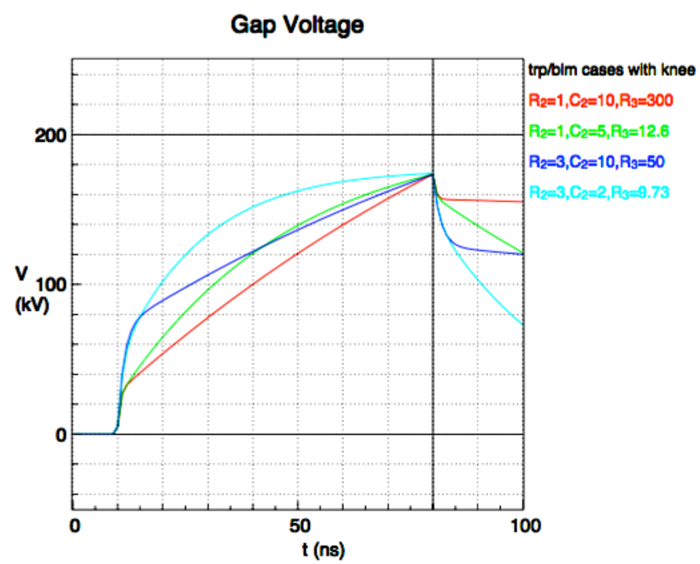
The compression section pulsers are based on simple passive circuits to generate a wide variety of waveforms



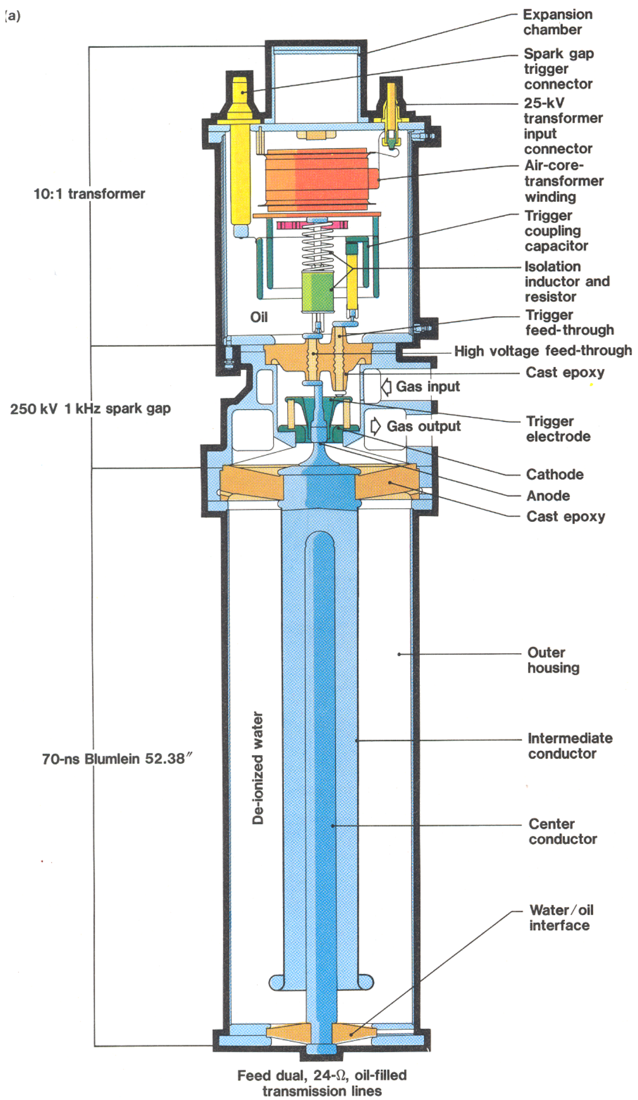
RL shaping networks

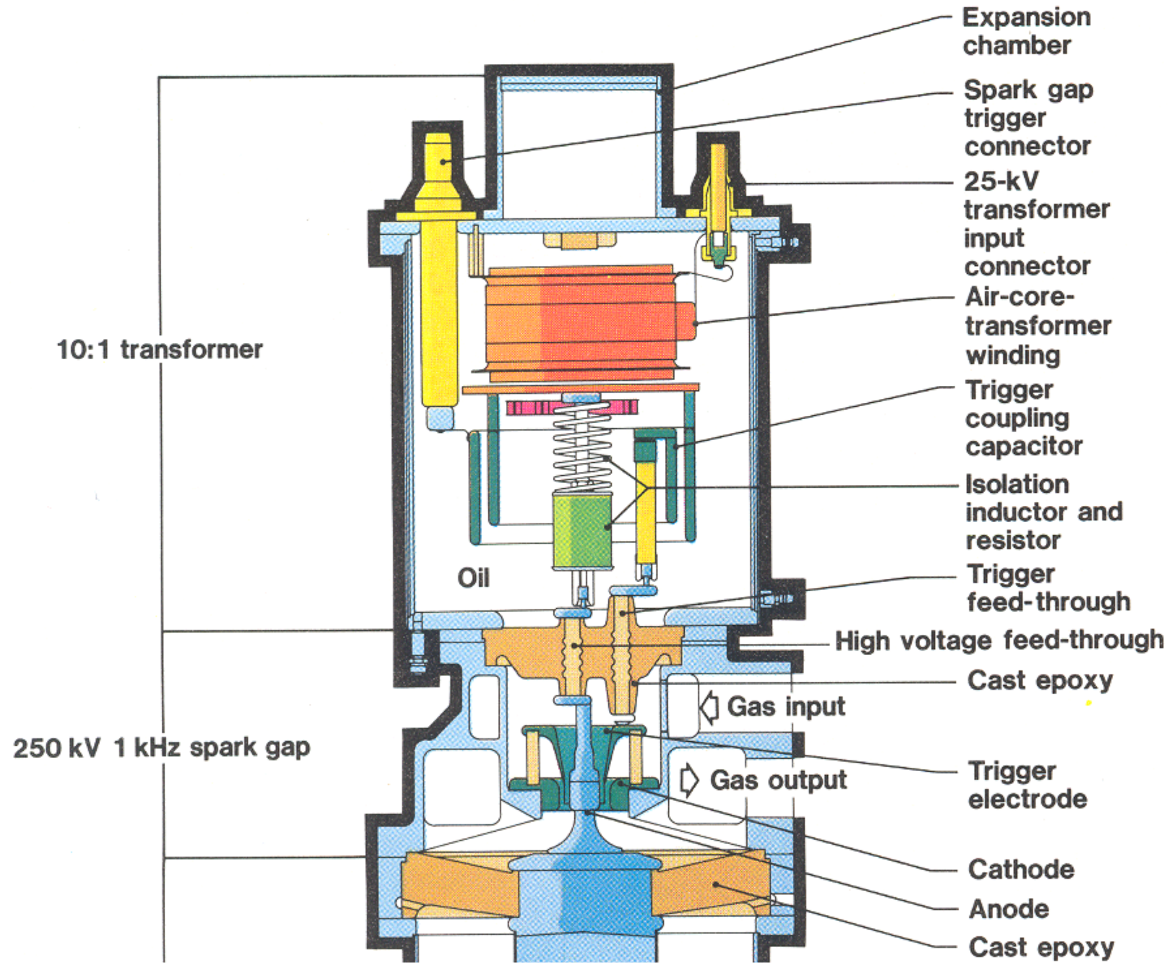


RC shaping networks



Existing ATA charging transformers, spark gaps, and Blumleins are used without modifications to the designs





Control System and Power Supply Count

- Control System (control and monitor power supplies, monitor machine status, initiate timing sequence, archive data, etc.)
  - Labview based user interface but requirements and architecture will be determined after a controls engineer has been hired (in process)
  - Have received proposals from 2 companies (backup solution)

POWER SUPPLIES	
injector	4
beam diagnostics	22
low energy cell reset	8
low energy cell pulser	8
switch chassis	7
cell solenoid pulsers	27
cell dipole pulsers	14
plasma source pulsers	6
final focus solenoid pulser	1
target diagnostics	12
TOTAL	**109**

Timing System and Trigger Channel Count

- Digital delay trigger generators
  - Modular PCI/cPCI/PXI or VME system with crates of cards
  - Request for bid will go out by the end of January

TRIGGERS	
injector pulsers	1
low energy cell reset	8
low energy cell pulser	8
switch chassis	7
spark gap trigger	7
cell solenoid pulsers	27
cell dipole pulsers	14
plasma source pulsers	6
final focus solenoid pulser	1
target diagnostics	6
digitizers	6
TOTAL	**91**

Data Acquisition System and Digitizer Channel Count

- Digitizers
  - Modular PCI/cPCI/PXI or VME system with crates of cards
  - Request for bid went out in December

V and I Monitors	QTY	Bandwidth	Sampling Rate	Memory	Vertical Resolution
cell solenoid pulser I (27 solenoids)	27	5MHz	10MS/s	128kB	8-bit
cell dipole pulser I (7 intercells with dipole pair)	14	5MHz	10MS/s	128kB	8-bit
final focus solenoid pulser I	1	5MHz	10MS/s	128kB	8-bit
low energy cell reset I	8	25MHz	50MS/s	128kB	8-bit
charging transformer V	7	25MHz	50MS/s	128kB	8-bit
plasma source pulser V	6	25MHz	50MS/s	128kB	8-bit
plasma source section I	24	25MHz	50MS/s	128kB	8-bit
injector extractor pulser V	1	500MHz	1GS/s	128kB	8-bit
beam diagnostics (8 intercells, 4 pickups each)	32	500MHz	1GS/s	128kB	8-bit
beam diagnostics (FC and scintillator in 3 locations)	9	500MHz	1GS/s	128kB	8-bit
cell V (12 cells)	12	500MHz	1GS/s	128kB	8-bit
beam diagnostics (2 intercells, 4 pickups each)	8	500MHz	2GS/s	128kB	8-bit
beam diagnostics (FC and scintillator in 1 location)	3	500MHz	2GS/s	128kB	8-bit
cell V (3 cells)	3	500MHz	2GS/s	128kB	8-bit
target diagnostics I	4	500MHz	2GS/s	128kB	8-bit
TOTAL CHANNELS	**159**				